Cyclotron Resonance in InMnAs Films and Heterostructures

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InMnAs Alloys and Heterostructures: First-grown III-V DMS

- InMnAs alloys and InMnAs/AlGaSb heterostructures
  - First grown III-V dilute magnetic semiconductor (DMS) system

    H. Munekata et al., Phys. Rev. Lett. 63, 1849 (1989).
- Combining semiconducting and magnetic properties - implementing spin degree of freedom in semiconductors - new device applications
  - Novel ferromagnetic semiconductor devices with high Curie temperatures, T_C
- Need to understand transport and optical properties
  - Band parameters (m^* and g-factor) have not been determined
- What is the effect of Mn ions on the band parameters?

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Effects of Mn on mass and g-factor

- Localized *d*-like electrons in Mn ions strongly influence:
  - Electrons in CB via *s*-*d* exchange interaction – α
  - Holes in VB via *p*-*d* exchange interaction – β
- Determining α and β is important to understand:
  - Mn-*e* states and mixing of delocalized and localized carrier states
- InMnAs is a narrow gap SC
  - Due to strong interband mixing – α and β are not independent
- The best way to determine α and β is CR and ESR but
  - No CR and ESR studies in III-V DMS systems
- We have made the first observation of CR in:
  - *n*-type films with various Mn content
  - *p*-type films and heterostructures with different T_C
  - *n*- and *p*-type InMnAs/InAs superlattices

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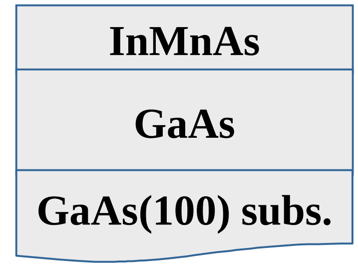
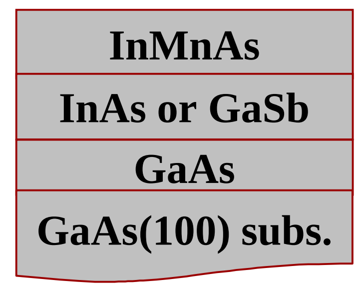
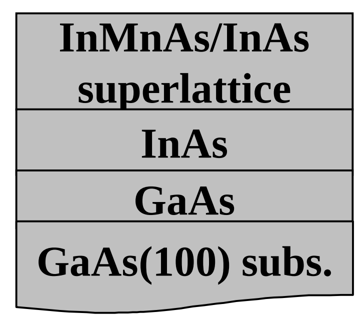
Samples

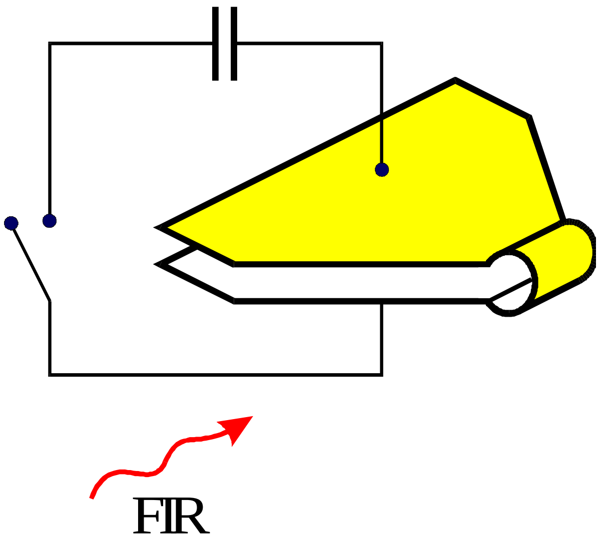
- *n*-type (paramagnetic)
  - $In_{1-x}Mn_xAs$
  - x = 0, 2.5, 5.0 and 12.0 %
  - μ ~ 450 cm^2/Vs
- *p*-type (ferromagnetic)
  - $In_{1-x}Mn_xAs/InAs$ $x = 2.5$ % $T_C < 10$ K
  - $In_{1-x}Mn_xAs/GaSb$ $x = 9.5$ % $T_C = 35$ K
- InMnAs/InAs superlattices
  - 5nm/5nm×101 periods
    - T_s = 300ºC → *p*-type
  - 5nm/5nm×85 periods
    - T_s = 200ºC → *n*-type

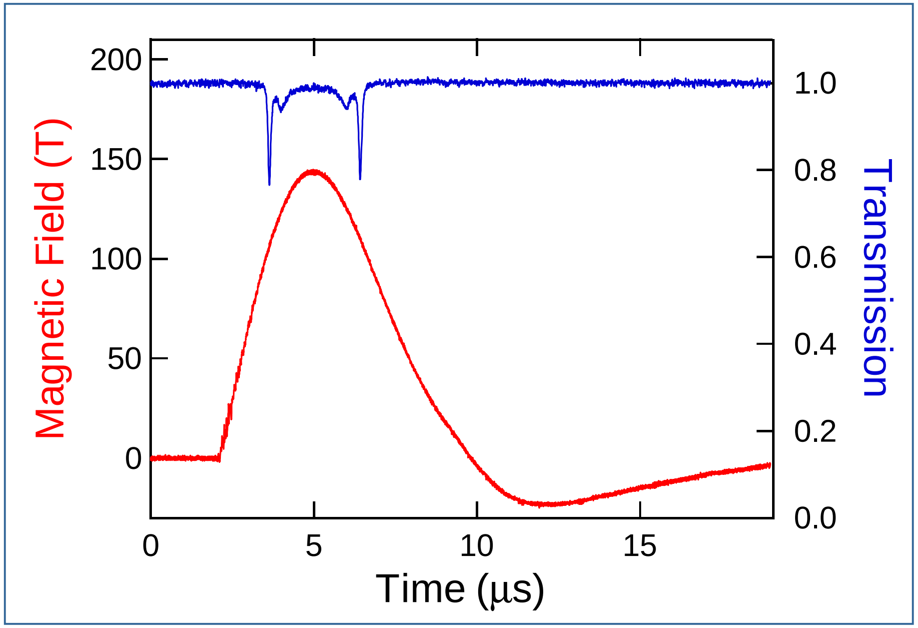






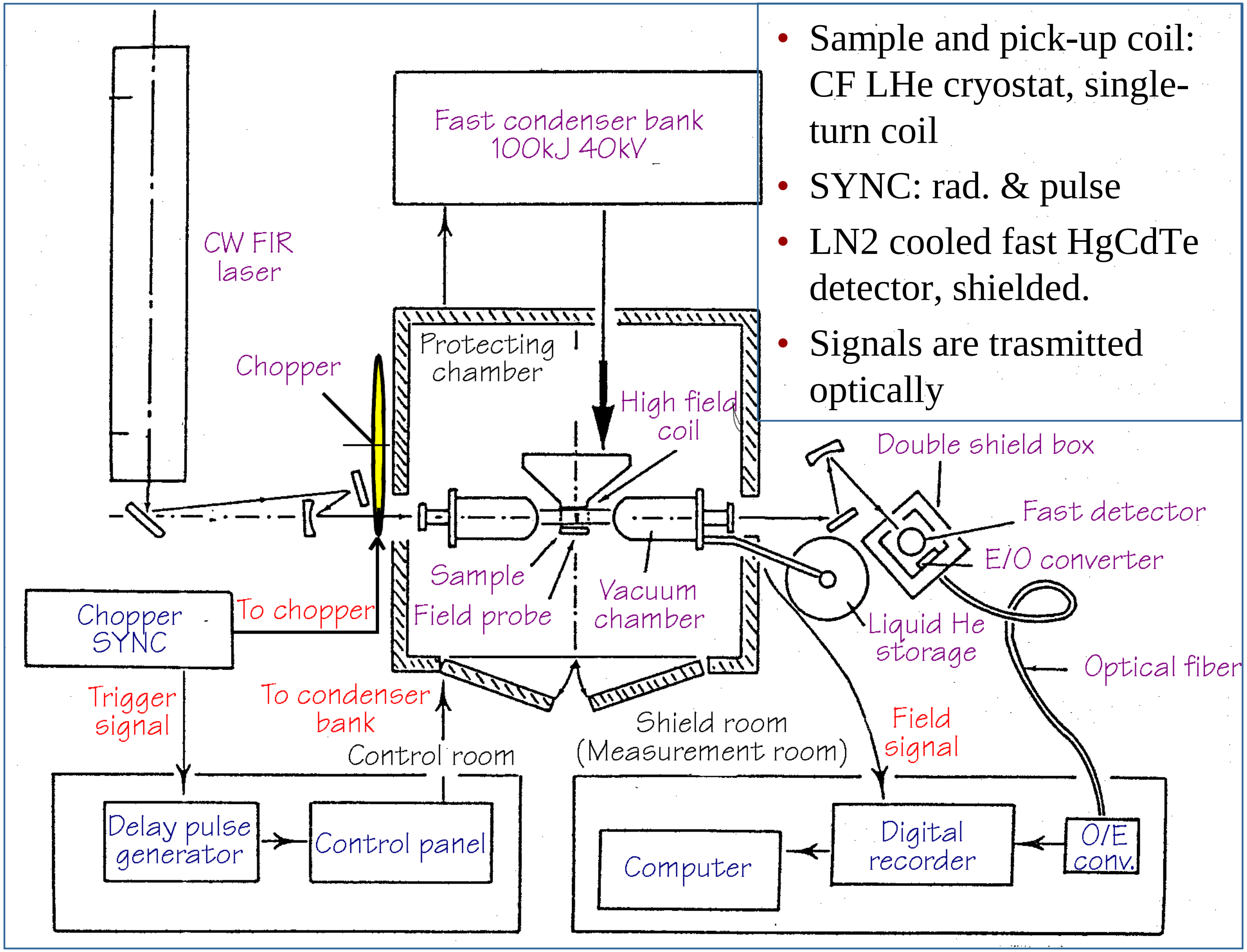
Megagauss cyclotron resonance
(with a destructive pulsed magnet)





- Megagauss Laboratory, Univ. of Tokyo
- Transmission is recorded twice, both on the up- and down-sweep
- Sample survives
  - many measurements on a single sample

Experimental setup

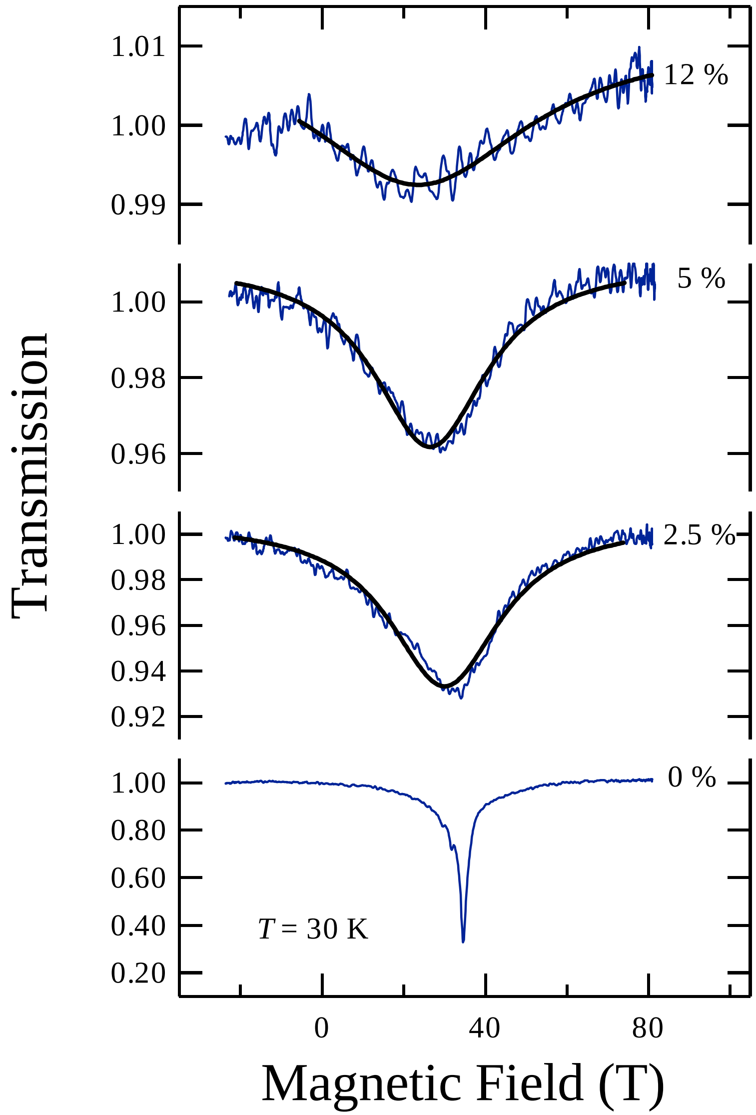


- Sample and pick-up coil: CF LHe cryostat, single-turn coil
- SYNC: rad. & pulse
- LN2 cooled fast HgCdTe detector, shielded.
- Signals are trasmitted optically

This facility can generate up to ~200T (2MG)!

CR in n-type $In_{1-x}Mn_xAs$

(T = 30 K, λ = 10.6 µm, e-active)

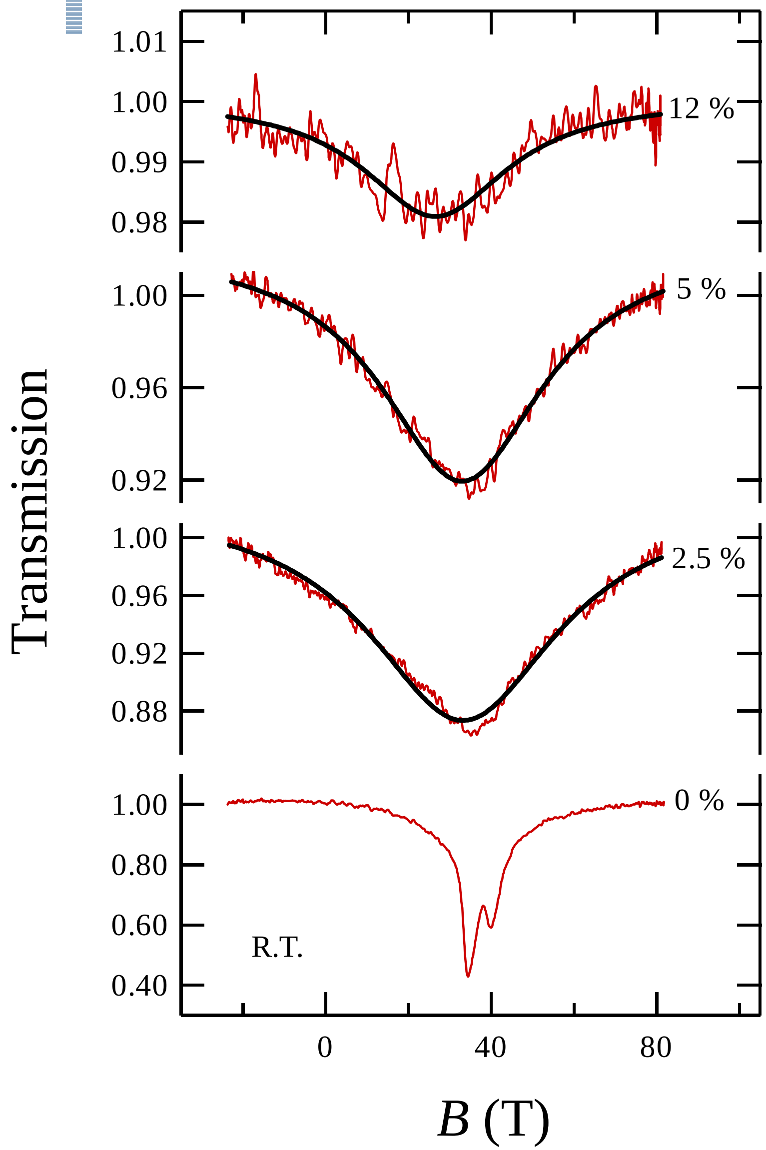


- All samples show pronounced absorption peaks and the peak position systematically shifts to lower magnetic fields with increasing Mn content
- Cyclotron masses:

x (%)	0	2.5	5	12
m_{CR} (m_0)	0.0342	0.0303	0.0274	0.0263

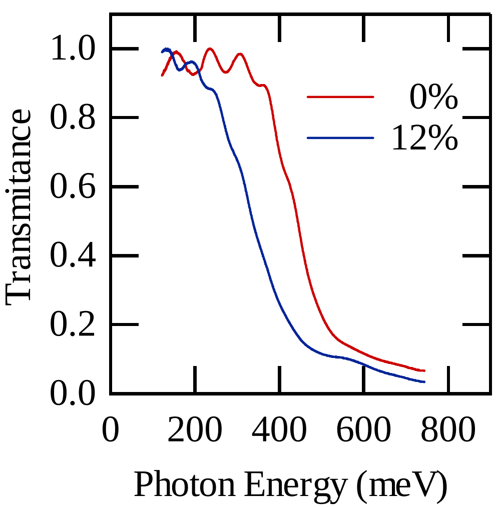
  - m_{CR} *decreases* by ~25%
  - CR: From LLL to 1^{st}LL @ 117 meV – values are larger due to non-paraboplicity
- The absorption strength (electron density) *decreases* with increasing x
  - Free e are provided by excess As, so increasing x results in compensation

Cyclotron Resonance in n-type $In_{1-x}Mn_xAs$
(Room temperature, λ = 10.6 μm, e-active)



x (%)	0	2.5	5	12
$m_{CR}\,(m_0)$	0.0341	0.0334	0.0325	0.0272

- Similar behavior at room T
- Non-parabolicity induced spin splitting of the CR peak in the reference sample
- FTIR: band gap E_g *decreases* with x



Effective Mass Theory
(calculations by Gary Sanders in Prof. Stanton's group)

- Pidgeon-Brown 8 x 8 bands method (including non-parabolicity) applied to $In_x\,Mn_{1-x}As$ with *B* along [001]
- *sd* and *pd* exchange interactions between delocalized *s* & *p* electrons and localized Mn *d* electrons with average spin, $\vec{S} = \langle S_z \rangle \hat{z}$.

$$\boxed{H_{sp-d} \propto J\,\sigma \cdot \left(x\,\langle S_z \rangle \hat{z} \right)}$$

- Exchange is parameterized by:

$$\boxed{\alpha = \frac{1}{\Omega}\langle S \,|\, J \,|\, S \rangle; \qquad \beta = \frac{1}{\Omega}\langle Z \,|\, J \,|\, Z \rangle}$$

- Narrow gap: both α and β are important in calculation of the CB LLs
- Estimate for InMnAs: $\beta = -0.98$ eV

Dietl et al. PRB **63**, 195205 (2001).

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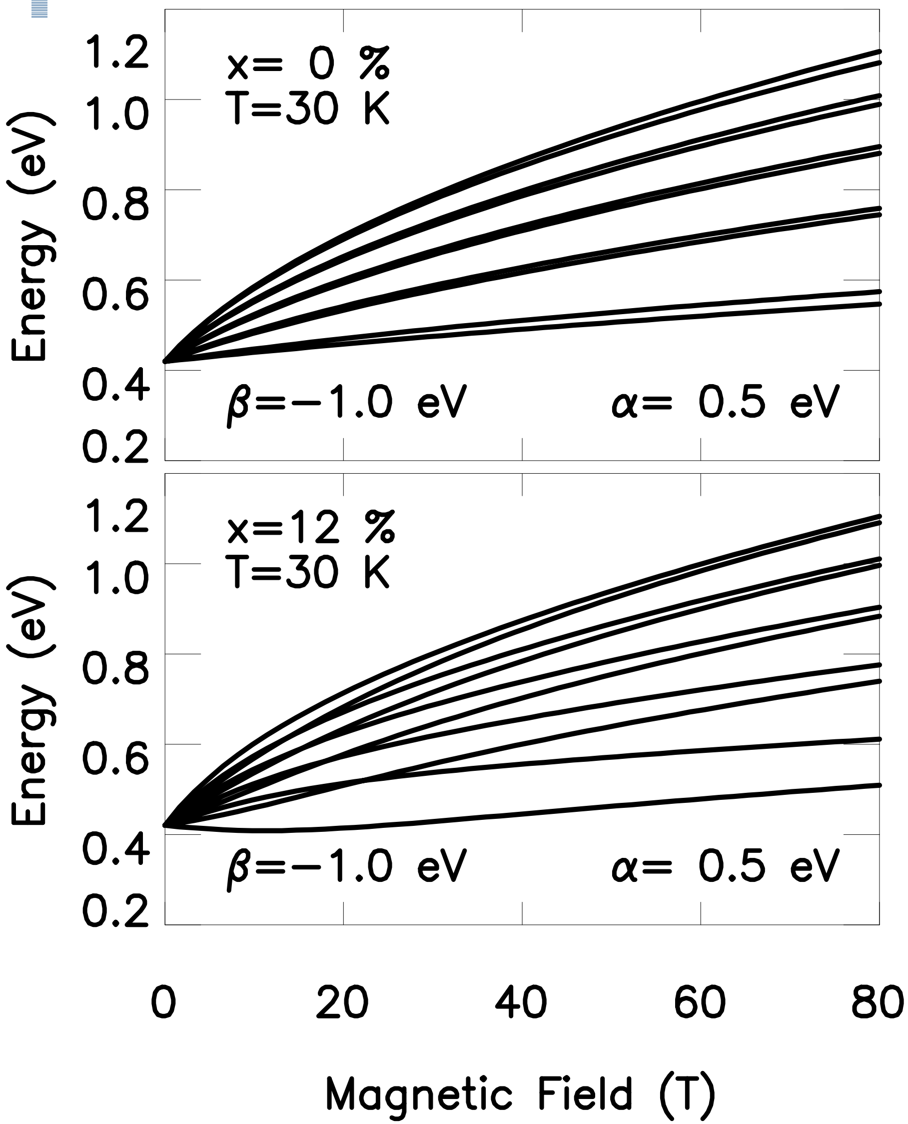
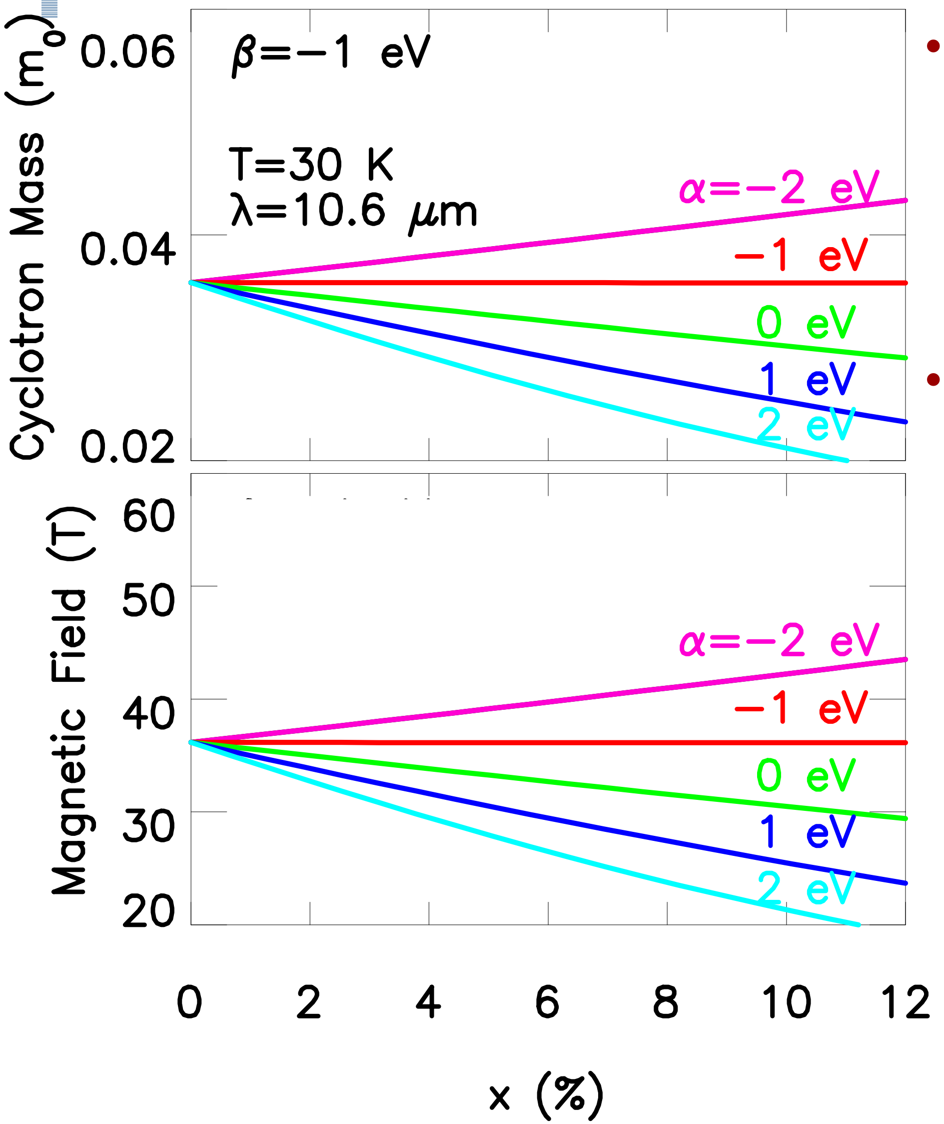
Electron Landau Levels



- Lowest five LLs in the CB for x = 0% and 12%
- We take β = -1.0 eV and α = 0.5 eV as values which best represent the observed trends
- Mass and g-factor strongly depend on energy and magnetic field

Cyclotron mass vs. Mn concentration



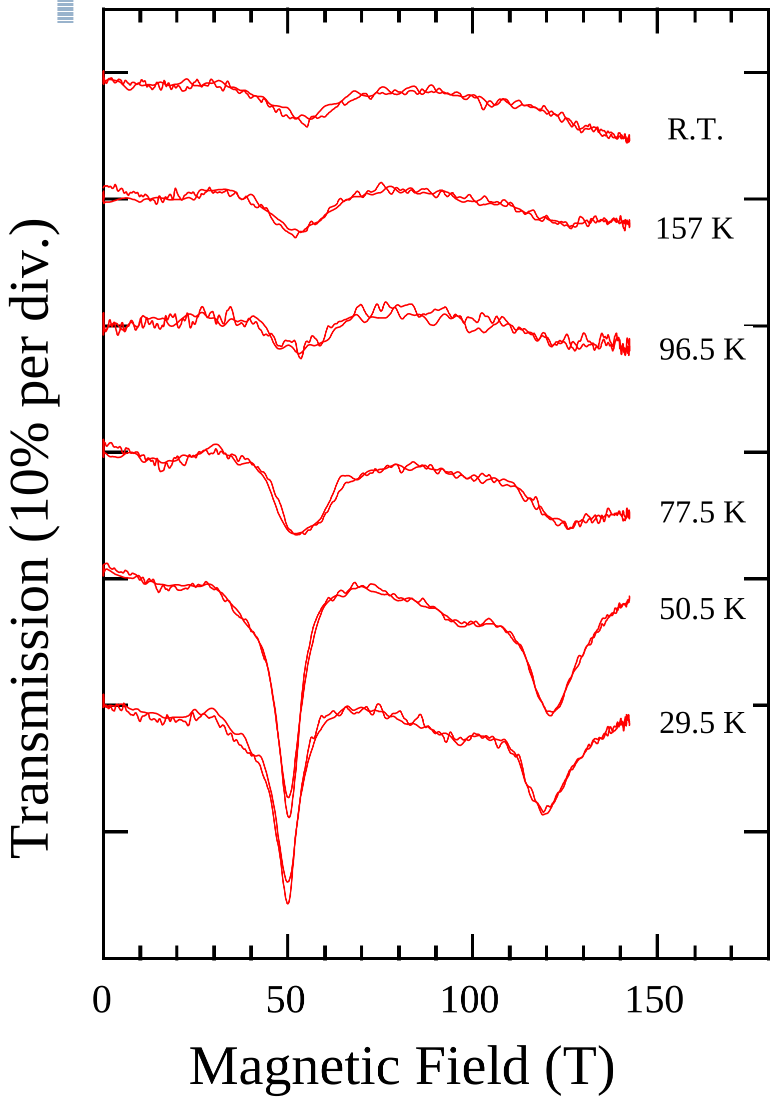
- When comparing with experiment both sign and values of α and β are important
  - good method to estimate these parameters
- α ~ -0.5 eV, β ~ 1.0 eV qualitatively explain the observe mass decrease

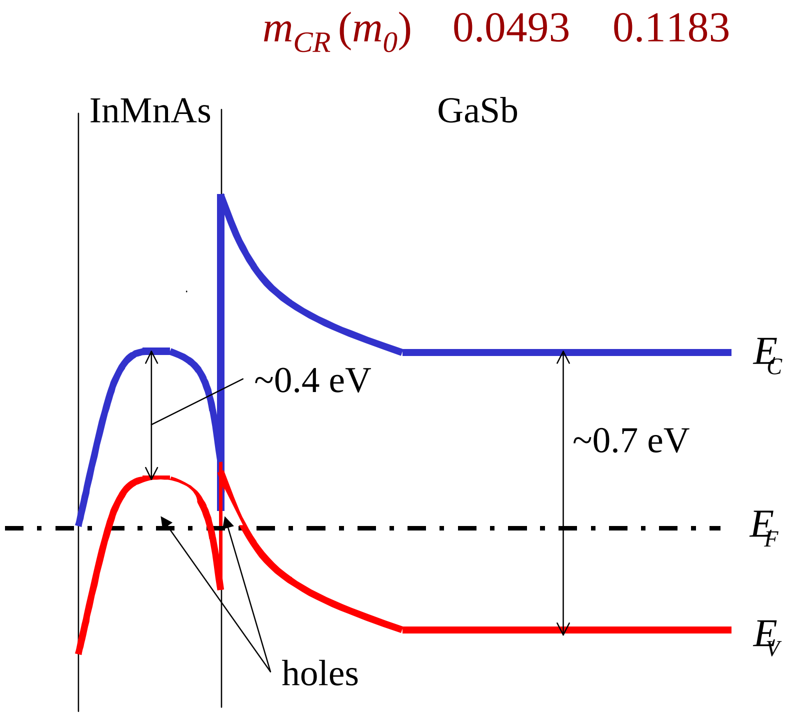
From previous studies on II-VI DMS:

- α and β have opposite sign
- |α| < |β|

CR in ferromagnetic *p*-type $In_{1-x}Mn_xAs$

(*T*-dependence, λ = 10.6 μm, *h*-active)





- Multiple absorption peaks which exhibit strong *T*-dependence
- Theoretical analysis under way

Summary: CR in InMnAs

- Electron cyclotron resonance in *n*-type $In_{1-x}Mn_xAs$
  Electron effective mass *decreases* with increasing Mn concentration, *x*.
- Modified Pidgeon-Brown model (8 x 8 band **k•p**)
  - successfully reproduced this behavior
  - allows determination of the alpha and beta parameters
    $\alpha = 0.5$ eV and $\beta = -1$ eV
- Hole cyclotron resonance in *p*-type $In_{1-x}Mn_xAs$
  - Multiple absorption peaks (both free and bound hole)
  - Strong temperature dependence
  - Further analysis should shed new light on the electron states in Mn acceptors